

APPENDIX A: DESCRIPTIONS OF MINERALS COATING THE FRACTURES OF YUCCA MOUNTAIN TUFFS

Zeolites

Zeolites describe a group of minerals characterized by an open framework of aluminosilicate tetrahedra. They are known as good sorbers because of the exchangeable cations within the channels of the framework structures. The common exchangeable cations in zeolites are sodium, calcium, and potassium (Deer et al. 1966).

Most zeolites are generally white but may be brown, red, pink, yellow, green, and blue. Their specific gravity is low (2.0–2.5) as a result of their open framework, and their hardness is moderate (3–5). Zeolites occur in regimes of low temperature and pressure. They are commonly found as secondary minerals resulting from alteration of volcanic rocks and as authigenic minerals within sedimentary units (Klein and Hurlbut 1985).

- **Analcime** is commonly white with some gray, green, red, and in rare cases, blue samples. It is an isometric mineral, usually found as trapezohedral crystals. Crystals tend to be anonymously biaxial with birefringent lamellar twinning. The hardness is 5.5 with a specific gravity of 2.7. The crystalline framework is comprised of combinations of 4- and 6-member rings of aluminosilicate tetrahedra. The channels have a minimum diameter of 2.2 Å (Deer et al. 1966). Analcime has a higher metamorphic-rock gradient than the other zeolites and is associated with the feldspathoids. In some references, it is not classified as a zeolite.
- **Chabazite** is commonly white with some yellow, pink, and red samples. It is a hexagonal mineral usually found as rhombohedrons with nearly cubic angles. The hardness ranges from 4 to 5, and the specific gravity from 2.05 to 2.15. The framework structure contains 4-, 6-, and 8-member rings of aluminosilicate tetrahedra. The channels have a minimum diameter of 3.8 Å (Meier and Olson 1992).
- **Erionite** is part of the chabazite group. It is a hexagonal, commonly acicular, fibrous mineral. It is one of the more siliceous zeolites. The crystalline framework is comprised of combinations of 4-, 6-, and 8-member rings of aluminosilicate tetrahedra. The channels have a minimum diameter of 3.6 Å (Meier and Olson 1992).
- **Heulandite** is commonly white with some samples being yellow and red. It is a monoclinic mineral, but crystals often display orthorhombic symmetry. Crystals are typically tabular. The hardness ranges from 3.5 to 4, and the specific gravity from 2.18 to 2.2. The framework is comprised of combinations of 5-, 6-, and 8-member rings of aluminosilicate tetrahedra. The channels have a minimum diameter of 3.3 Å (Meier and Olson 1992). Heulandite has low bond strength in one direction and therefore loses structural integrity with dehydration (Breck 1974).
- **Clinoptilolite** is part of the heulandite group. It is monoclinic with typically tabular to platy crystals. In contrast to heulandite, clinoptilolite is stable under dehydration. The crystalline framework is similar to heulandite (Breck 1974).
- **Stellerite** is the calcium end member of the stilbite solid solution, which is part of the heulandite group. It is usually transparent to white and rarely yellow, brown, or red. The crystal system is monoclinic, typically in platy, sheetlike aggregates, which may also form cruciform penetration twins. The hardness ranges from 3.5 to 4, and the specific gravity is 2.2. The framework is comprised of combinations of 4-, 8-, and 10-member rings

of aluminosilicate tetrahedra. The channels have a minimum diameter of 2.7 Å (Meier and Olson 1992).

- **Mordenite** is usually transparent to white with a distinctive waxy luster. It is an orthorhombic mineral, typically in laths or fibrous crystals. It is a high-silica zeolite. The framework is comprised of combinations of 5-, 8-, and 12-member rings of aluminosilicate tetrahedra. The channels have a minimum diameter of 2.6 Å (Meier and Olson 1992).
- **Phillipsite** is an orthorhombic mineral commonly displaying cruciform penetration twins. Its hardness ranges from 4 to 4.5. The framework is comprised of combinations of 4- and 8-member rings of aluminosilicate tetrahedra. The channels have a minimum diameter of 3.0 Å (Meier and Olson 1992).

Silica

The silica minerals are part of a mineral group referred to as tectosilicates, of which zeolites are also a member. Tectosilicates define a mineral classification in which all four oxygen atoms of a silica tetrahedron (SiO_4) are shared with other neighboring silica tetrahedra. These minerals are generally very strong, stable structures with a silicon-to-oxygen ratio of 1 to 2 (Klein and Hurlbut 1985).

- **Quartz** is one of the most abundant of all minerals. It is generally transparent to white, but it comes in a host of different colors, varieties, and names. Quartz is hexagonal with enantiomorphous crystals in the trigonal trapezohedral class of the rhombohedral subsystem. Striations occur perpendicular to the long axis. The hardness is 7, and the specific gravity is 2.65. Of the nine known polymorphs of SiO_2 , α -quartz, or low quartz, is the polymorph that is stable below 574 °C and one atmosphere pressure (Klein and Hurlbut 1985).

- **Tridymite** is one of the high-temperature polymorphs of silica. The mineral is stable between 870 and 1470 °C. It is commonly found in vugs and cavities of siliceous volcanic rocks as tabular crystals or scales. The lower-temperature α -tridymite is in the orthorhombic crystal system, whereas the higher-temperature β -tridymite is hexagonal (Klein and Hurlbut 1985).
- **Cristobalite** is the highest-temperature polymorph of silica. It is commonly formed as a devitrification product of siliceous volcanic glass. Similarly to tridymite, cristobalite is found in vugs and cavities of siliceous volcanic rocks but usually as white octahedrons. The lower-temperature α -cristobalite is in the tetragonal crystal system, whereas the higher-temperature β -cristobalite is isometric (Klein and Hurlbut 1985).
- **Opal** is actually not a mineral but a mineraloid, because it lacks a crystalline structure. It is usually white but can be found in any color. Opal is best known for its property of opalescence. It is comprised of packed spheres of silica and water molecules that can range in content from 3 to 20 per cent. The hardness varies from 5.5 to 6.5, and the specific gravity varies from 2.0 to 2.2 (Klein and Hurlbut 1985).
- **Feldspars** are the most abundant and widespread of the minerals, constituting 60 per cent of the earth's crust. They are usually white but can be pink, orange, blue, and green. The mineral is comprised of a framework of aluminosilicate tetrahedra with large voids that house the large cations of potassium, calcium, and sodium. Feldspars are generally classified into two groups: **K-feldspars** and **plagioclase**. The K-feldspars have identical chemical constituents but differ in structural states, defined as order or disorder, that are a result of their cooling history. Rapidly cooled K-feldspars produce **sanidines**, where-

as slow cooling creates **orthoclase** and **microcline**. Plagioclase nomenclature is based on chemical variances of a solid-solution series. The sodic end member is **albite**; the calcic end member is **anorthite**; other compositions have various names. The feldspars all have a hardness of 6 and a specific gravity that ranges from 2.55 to 2.76 (Klein and Hurlbut 1985).

Clays

The term “clays” is somewhat ambiguous. Clays are described as finely crystalline or amorphous hydrous silicates with metacolloidal properties (Deer et al. 1966). They are loosely classified as phyllosilicates that have a platy habit due to a prominent single cleavage. They commonly have low specific gravity and flexible elasticity. Their structure consists of composite layers built from components with tetrahedrally and octahedrally coordinated cations (Klein and Hurlbut 1985). The phyllosilicates are grouped into two major divisions: **dioctahedral** and **trioctahedral**. In dioctahedral clays, only two-thirds of the sites in the octahedral sheets are occupied, whereas in trioctahedral clays, all are occupied (Deer et al. 1966). Clays are ordinarily produced as an alteration or weathering product from primary minerals. The primary interest in clays is both their ability to absorb water and their ionic exchange.

- **Smectites** is a general name for the group of swelling clays. They are a three-layer mineral comprised of two silica tetrahedral sheets and a central alumina octahedral sheet. Charge deficiencies exist between octahedral and tetrahedral sheets, which are balanced by exchangeable cations. The unique, reversible swelling property of smectites is a result of infiltration of water and other polar molecules into the region between the sheets, causing expansion (Deer et al. 1966).
- **Sepiolite** and **palygorskite** are rarer than other clays and have a hornblende-like chain

structure of silica tetrahedra. They are able to absorb and retain water, a capability that derives from a structure consisting of inverted linked ribbons of silica tetrahedra that form elongate rectangular boxes. Water is able to fill the channels produced on the elongated sides of the boxes. Furthermore, in this structure, the octahedral sheets are discontinuous and contain cations, generally Mg^{2+} , at the edges. These cations, besides being susceptible to cation exchange, are also able to hold water molecules. This structure tends to give the minerals a fibrous, fuzzy appearance in hand-samples (Deer et al. 1966).

- **Illite** is a commonly used description of non-expanding phyllosilicates with a basal d-spacing of 10 Å. Approximately 15 per cent of the silicon atoms from the silica tetrahedra are replaced by aluminum atoms, a change that results in a charge deficit that is balanced by potassium cations between the illite sheets. Potassium ions are stacked, allowing no potential for expansion (Klein and Hurlbut 1985).

Oxides and Hydroxides

The oxide minerals are naturally occurring compounds in which one or more metals is bonded with oxygen. (We have listed quartz and its polymorphs, the most common of all oxides, separately because their structures are more appropriately associated with other silica-oxide compounds.)

The oxide minerals are generally simple in composition and structure (Palache et al. 1944); however, some varieties of manganese oxide (MnO) have complex tunnel-structures, such as todorokite, romanechite, and coronadite/hollandite (Bish and Post 1989; Chukhrov et al. 1985b, 1987). Most of the manganese-oxide minerals appear as amorphous to fine-grained black coatings that cannot be distinguished from one another except by x-ray diffraction, electron microdiffraction, or energy-dispersive analysis. Oxides generally have strong ionic bonds, giving them a hard, dense, and often

refractory characteristic. They are often found as residual-detritus grains in sediments, commonly from igneous or metamorphic paragenesis (Klein and Hurlbut 1985). The hydroxides, as opposed to the oxides, are generally found as secondary minerals with low hardness and density. They are bonded to either hydroxyls or water molecules, which tends to create a weaker structure than that of the oxides (Palache et al. 1944).

Manganese oxides

- **Aurorite** generally occurs as an irregular mass but is also found as platy or scaly grains, commonly with black calcite. Large grains of aurorite are generally less than 8 μm (Radtko et al. 1967).
- **Cryptomelane** is commonly found as a fine-grained mass with prominent conchoidal fractures. Botryoidal as well as radial fibrous habits with prominent cleavage are known but are uncommon. The color of the mineral is black with a brownish-black streak. The hardness is 6 to 6.5; however, the hardness of the masses may be as low as 1 (Richmond and Fleischer 1943).
- **Hollandite** is a black tetragonal mineral, usually found as a fine-grained mass. The habit, although generally massive, can also be found as short prismatic crystals terminated by a flat pyramid and as fibrous crystals. Cleavage is prismatic and distinct. The mineral has a black streak and a hardness of 6 on the crystal faces. The hardness can be significantly less from exposures of the fracture (Palache et al. 1944).
- **Coronadite** is isostructural with hollandite. It is a black mineral with a habit generally found as a fine-grained mass; however, botryoidal crusts or fibrous structures are also known. The mineral has a brownish-black streak and a hardness of 4.5 to 5 (Palache et al. 1944).
- **Lithiophorite** is generally found as a shiny to dull-black mineral. Its name was derived from the belief that it contained lithium as one of its key components; however, now it is known that the mineral can have varieties that are virtually lithium free and that cobalt and nickel play a more essential role in its make-up. The structure of the mineral is analogous to gibbsite (Chukhrov et al. 1985a).
- **Rancieite** is a soft, reddish-black to black mineral. The structure contains disordered stacking of MnO_6 hexagonal layers or octahedras of $\text{Mn}(\text{OH})_6$ with a cation, typically Ca^{2+} , located between the layers (Barrese et al. 1986).
- **Romanechite** is generally found as a dull iron-black orthorhombic mineral. Its habit is commonly fine-grained masses, but it can also be found as botryoidal or reniform structures. The streak is shiny brownish-black to black and has a hardness of 5 to 6 (Palache et al. 1944).
- **Todorokite** is generally found as a metallic-black monoclinic or orthorhombic mineral. It generally occurs as spongy banded and reniform aggregates of small lathlike crystals (Palache et al. 1944).
- **Pyrolusite** is the most common of the manganese-oxide minerals. Its best field characteristic is its sooty-black streak. The mineral is tetragonal but is generally found as massive structures. It is also commonly found as fibrous, acicular, radial, or dendritic growths on fracture exposures. The hardness is 6 to 6.5 with a perfect cleavage in one direction (Klein and Hurlbut 1985).

Iron oxides

- **Hematite** is a common iron oxide and can range from a metallic steel-gray to an earthy brownish-red. The hardness ranges from 5 to 6, and the specific gravity from 4.9 to 5.3. The fracture is uneven to splintery. The crys-

tal system is hexagonal with many common forms, such as tabular-striated growths, granular, radiated, reniform, compact, micaceous, botryoidal, and earthy. It can be identified by its red streak and hardness (Klein and Hurlbut 1985).

system is isometric, commonly found as cubes, octahedra, and sometimes as dodecahedra. Calcite is easily identified by its crystal shape, hardness, fluorescent properties, and waxy luster (Klein and Hurlbut 1985).

- **Magnetite** is generally a metallic iron-black mineral with a dark black streak. The hardness ranges from 5.5 to 6.5, and the specific gravity from 4.9 to 5.2. The fracture is uneven to subconchoidal. The crystal system is isometric, usually found as octahedrons or striated dodecahedrons. Magnetite's field characteristics include its dark black streak and magnetic property (Klein and Hurlbut 1985).

Carbonates

The carbonates contain an anionic CO_3^{2-} structural unit in which the three oxygen atoms form an equilateral triangle with the carbon atom at the center. Covalent bonds describe the oxygen-carbon unity, whereas bonds to this group are generally ionic (Klein and Hurlbut 1985).

- **Calcite** is the most common of all the carbonate group. It is generally white to transparent but can come in all the hues of the rainbow. It has perfect cleavage in three directions, giving it a common rhombohedral shape. The crystal system is hexagonal. Calcite has a hardness of 3 and a specific gravity is 2.7. It is best identified by its rhombohedron shape and by its vigorous effervescent effect when exposed to acid (Klein and Hurlbut 1985).

Halides

The halides represent a group in which a halogen is the dominant anionic component.

- Fluorite occurs in any color. It has a hardness of 4 with perfect cleavage in four directions. The specific gravity is 3.0 to 3.2. The crystal

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